

*An Introduction to the Biology of*

# *Marine Life*

James L. Sumich

Fifth Edition

EKU

USED BOOK

COURSE: BIO 340  
AUTHOR: SUMICH  
TITLE: INTRO TO BIOLOGY OF MARINE LIFE  
0-697-05143-9 \$32.95

If Label Removed

NO REFUND

*An Introduction to the Biology of*  
***Marine Life***

Fifth Edition

James L. Sumich

Grossmont College



Wm. C. Brown Publishers

### **Book Team**

Editor *Kevin Kane*  
Developmental Editor *Margaret J. Manders*  
Production Editor *Renee A. Menne*  
Designer *Mark Elliot Christianson*  
Art Editor *Margaret Rose Buhr*  
Photo Editor *Carrie Burger*  
Visuals Processor *Amy L. Saffran*



### **Wm. C. Brown Publishers**

President *G. Franklin Lewis*  
Vice President, Publisher *George Wm. Bergquist*  
Vice President, Operations and Production *Beverly Kolz*  
National Sales Manager *Virginia S. Moffat*  
Group Sales Manager *Vincent R. Di Blasi*  
Vice President, Editor in Chief *Edward G. Jaffe*  
Marketing Manager *Paul Ducham*  
Advertising Manager *Amy Schmitz*  
Managing Editor, Production *Colleen A. Yonda*  
Manager of Visuals and Design *Faye M. Schilling*  
Production Editorial Manager *Julie A. Kennedy*  
Production Editorial Manager *Ann Fuerste*  
Publishing Services Manager *Karen J. Slaght*

### **WCB Group**

President and Chief Executive Officer *Mark C. Falb*  
Chairman of the Board *Wm. C. Brown*

Cover photo © F. Stuart Westmorland/Allstock, Inc.

Copyright © 1976, 1980, 1984, 1988, 1992 by Wm. C. Brown Publishers. All rights reserved

Library of Congress Catalog Card Number: 91-71936

ISBN 0 697 05143 9 (Paper)  
0 697 13515 2 (Cloth)

No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of the publisher.

Printed in the United States of America by Wm. C. Brown Publishers, 2460 Kerper Boulevard, Dubuque, IA 52001

10 9 8 7 6 5 4 3 2 1

# Preface

*An Introduction to the Biology of Marine Life* was written to satisfy the demand for an introductory college-level text dealing with the biology of marine organisms. Recent developments in the field of marine biology have shown that courses in this subject provide an exciting and effective framework for illustrating basic biological principles. As a result, marine biology courses for the nonmajor or premajor student have become increasingly popular.

This text is written for the introductory marine biology student. No previous knowledge of marine biology is assumed. However, some exposure to the basic concepts of biology is helpful. Selected groups of marine organisms are used to develop an understanding of biological principles and processes that are basic to all forms of life in the sea. To build on these basics, information dealing with several aspects of taxonomy, evolution, ecology, behavior, and physiology of selected groups of marine organisms is presented. I have intentionally avoided adopting one of these major subdivisions as the framework of this text. Biology is an inclusive term, and a student's initial venture into this field should provide some flavor of the mix of disciplines that constitutes modern biology.

## ***Scope of Subject Matter***

This text includes more material than the typical student can assimilate in a semester. Instructors can select and mold the material to match their teaching styles and time limitations. The accompanying instructor's manual provides suggestions for use of this text, with judicious use of outside supplementary readings, in a two-quarter or two-semester course.

## ***Sequence of Topics***

As in most textbooks, each topic is developed after all have been first introduced in a general overview. Consequently, the sequence of topics is somewhat arbitrary and is intended to be flexible. The first chapter consists of an intro-

duction to the marine environment. Chapter 2 examines the general features of life in the sea and how it has evolved to the present. Chapter 3, a survey of marine animal groups, is included here to avoid cumbersome definitions and descriptions in later discussions. Chapters 4 and 5 describe marine primary producers and examine the major factors that shape the pattern of marine primary productivity. Chapter 6 discusses estuaries as a reduced-scale analogy of the world ocean, its inhabitants, and their interactions. Chapters 7, 8, 9, and 10 emphasize the roles of marine organisms in divergent marine communities. Chapters 11 and 12 examine structural and physiological adaptations necessary to adequately fill those roles. The final two chapters offer a perspective for understanding the effects of human intervention upon marine ecosystems, including fishing (chapter 13) and pollution (chapter 14).

## ***Student Aids***

Each chapter contains numerous illustrations, graphs, and charts to assist students in visualizing the concepts presented. End-of-chapter summaries, questions for discussion, and supplementary reading lists encourage further in-depth exploration of covered topics. Additional references, listed at the end of the text, will be useful to students who have the enthusiasm and communication skills necessary to cope with the challenges of reading original literature.

## ***Supplementary Materials***

### ***Instructor's Manual***

The Instructor's Manual offers a variety of course schedules, chapter summaries, film and video sources, and sample test questions for each chapter.

### ***Transparencies***

Fifty two- and five-color acetate transparencies are available with this text. The transparencies are taken from the text and represent figures that merit extra visual review and discussion. These images can also be ordered as a slide set.

### ***TestPak***

**web** TestPak, a free, computerized testing service, simplifies testing while offering you flexibility. Two convenient TestPak options are available:

—Use your Apple® IIe, Apple® IIc, Macintosh or IBM PC to pick and choose test questions, edit them, and add your own questions. We can send you program and test item diskettes for this purpose.

—If you don't have a microcomputer, pick and choose your questions via our call-in/mail-in service. Within two working days of your request, we will put a test master, a student answer sheet, and an answer key in the mail to you. Call-in hours are 8:30–5:00 CST, Monday through Friday.

## ***Materials for Field Study***

Since I have avoided regional limitations where practical, this text is not designed for use as a detailed field guide for local marine organisms; however, several regional identification and field guides are listed in Appendix C. A companion text, *Laboratory and Field Investigations in Marine Biology*, by J. L. Sumich and G. H. Dudley, is available for courses emphasizing field or laboratory experiences.

## ***New to this Edition***

The widespread and positive reception of the four previous editions of this text continues to be encouraging. This edition represents a continuing effort to better meet the needs of those who use the text. The many suggestions and comments from readers have been considered in the changes that were made. Two new chapters, chapter 9 (Coral Reefs) and chapter 14 (Ocean Pollution), have been added. Information on deep-sea hot springs and their associated bacterial production, primary productivity in polar oceans, air-breathing tetrapod groups, and many other topics have been added or expanded significantly. Most existing illustrations have been revised, and numerous new ones have been added, all with full-color presentation, to better complement the text material.

## ***List of Reviewers***

The following critical reviewers provided in-depth analyses of individual chapters and made many valuable suggestions concerning the final shape and content of the text:

Brenda Blackwelder, <i>Central Piedmont Community College</i>	Donald Munson, <i>Washington College</i>
Susan Cormier, <i>University of Louisville</i>	Joel Ostroff, <i>Brevard Community College</i>
Sheldon Dobkin, <i>Florida Atlantic University</i>	Richard A. Roller, <i>University of Wisconsin-Stevens Point</i>
J. Nicholas Ehringer, <i>Hillsborough Community College</i>	Mary Beth Saffo, <i>University of California-Santa Cruz</i>
Robert T. Galbraith, <i>Crafton Hills College</i>	Cynthia C. Stong, <i>Bowling Green State University</i>
Hal M. Genger, <i>College of the Redwoods</i>	Jefferson T. Turner, <i>Southeastern Massachusetts University</i>
Lynn Hansen, <i>Modesto Jr. College</i>	Richard Turner, <i>Florida Institute of Technology</i>
Lester Knapp, <i>Palomar College</i>	Jacqueline Webb, <i>New York St. College of Vet. Med., Cornell University</i>
Matthew Landau, <i>Stockton State College</i>	Robert Whitlatch, <i>University of Connecticut</i>
Cynthia Lewis, <i>San Diego State University</i>	Richard B. Winn, <i>Duke University Marine Laboratory</i>

## Market Research Respondents

We would like to thank the following adopters of the third edition for their help in preparing the current edition. Each contributed greatly to our understanding of the relative strengths and weaknesses of the third edition.

Genevieve Anderson, <i>Santa Barbara City College</i>	Richard S. Kelly, <i>SUNY at Albany</i>
Jonathon N. Baskin, <i>Cal Poly University, Pomona</i>	Robert W. Kelly, <i>Furman University</i>
Paul A. Billeter, <i>Charles County Community College</i>	William T. Krauss, <i>Los Angeles Valley College</i>
A. D. Brant, <i>Calvin College</i>	David A. Krupp, <i>Windward Community College</i>
David B. Campbell, <i>University of New Hampshire</i>	Jacqueline Lane, <i>Pensacola Junior College</i>
James L. Campbell, <i>Los Angeles Valley College</i>	Carolyn G. Lebsack, <i>Linn-Benton Community College</i>
Raymond D. Clarke, <i>Sarah Lawrence College</i>	Alan C. Miller, <i>California State University-Long Beach</i>
S. M. Cormier, <i>University of Louisville</i>	Harold R. Milliken, <i>Loma Linda University</i>
Angela Cristini, <i>Ramapo College of New Jersey</i>	W. J. Menkel, <i>Santa Clara University</i>
Sheldon Dobkin, <i>Florida Atlantic University</i>	John P. Manning, <i>Massasoit Community College</i>
Donald Dorfman, <i>Monmouth College</i>	Michael S. Murray, <i>Brookdale Community College</i>
William Fox, <i>Ventura College</i>	Steve Murray, <i>California State University-Fullerton</i>
Harry W. Freeman, <i>College of Charleston</i>	Phillip A. Nickel, <i>California Lutheran University</i>
Greta A. Fryxell, <i>Texas A &amp; M University</i>	June K. Ramsey, <i>Pensacola Junior College</i>
Hal M. Genger, <i>College of the Redwoods</i>	Brian R. Rivest, <i>SUNY at Cortland</i>
Malcolm S. Gordon, <i>U.C.L.A.</i>	L. O. Sorensen, <i>Pan American University</i>
Mark Gould, <i>Roger Williams College</i>	Carol A. Stepien, <i>University of San Diego</i>
G. S. Grantham, <i>College of the Redwoods</i>	Richard A. Snyder, <i>University of Maryland</i>
Philip F-C Greear, <i>Shorter College</i>	Susan O. van Loon, <i>Our Lady of Holy Cross College</i>
N. E. Grossnickle, <i>Grand Canyon College</i>	Leland Van Fossen, <i>DeAnza College</i>
James D. Haddock, <i>Indiana University-Purdue University at Fort Wayne</i>	Thomas A. Wayne, <i>Lane Community College</i>
E. C. Haderlie, <i>Naval Postgraduate School</i>	Judith Ann Williams, <i>Hawaii Pacific College</i>
Bernard F. Hanke, <i>Brunswick Technical College</i>	P. Kelly Williams, <i>University of Dayton</i>
Shelly R. Johnson, <i>Pasadena City College</i>	Ray E. Williams, <i>Rio Hondo College</i>
Robert A. Jordan, <i>Hampton University</i>	W. Herbert Wilson, Jr., <i>Northeastern University</i>
Dennis L. Kelly, <i>Orange Coast College</i>	Melvin B. Zucker, <i>Skyline College</i>

## ***Acknowledgments***

Much credit for the development of this text goes to students and instructors who have used previous editions and have offered valuable comments and criticisms. I thank my instructors of the past and colleagues of the present for their contributions to my education and to this book. Special thanks also go to the many individuals and institutions that graciously supplied many of the photographs. Most of the biological illustrations are the work of a fine artist, Steve Haney. Finally, I thank my present and former students for their interest and enthusiasm in discovering rewarding methods of communicating this information.

James L. Sumich



# Contents

Preface *viii*

## Chapter 1

### *The Ocean as a Habitat 1*

The Changing Marine Environment 2  
*Box 1* Three Voyages in Different Dimensions 6  
The World Ocean 9  
Properties of Seawater 14  
  Pure Water 14  
    Viscosity and Surface Tension 16  
    Density-Temperature Relationships 16  
    Heat Capacity 17  
    Solvent Action 18  
Seawater 19  
  Dissolved Salts 19  
  Marine Temperatures 21  
  Salinity-Temperature-Density Relationships 21  
  Dissolved Gases and Acid/Base Buffering 23  
  Dissolved Nutrients 26

The Ocean in Motion 26  
  Waves 26  
  Surface Currents 27  
  Vertical Water Movements 31  
Classification of the Marine Environment 33  
Summary 34  
Review Questions 35  
Questions for Further Discussion 35  
Suggestions for Further Reading 35

## Chapter 2

### *Some Ecological and Biological Concepts 37*

The Cellular Structure of Life 38  
*Box 2* Our Planetary Greenhouse 40  
Adaptations of Marine Life 41  
  The Value of Sex 43  
  Salinity Effects 45  
  Temperature Effects 48  
  Trophic Relationships 48  
Spatial Distribution 55  
The General Nature of Marine Life 58  
Summary 59  
Review Questions 60  
Questions for Further Discussion 60  
Suggestions for Further Reading 60

## Chapter 3

### *An Overview of Marine Animals 61*

Taxonomic Classification 62  
*Box 3* Biochemical Taxonomy 63  
The Protozoans 67  
  Sarcomastigophora 67  
  Ciliophora 70  
An Evolutionary Sideline 71  
  Porifera 71  
Radial Symmetry 73  
  Cnidaria 73  
  Ctenophora 74  
Bilateral Symmetry 76  
  Platyhelminthes 76  
  Nemertina 76  
  Gastrotricha and Kinorhyncha 77  
  Priapulida and Nematoda 77  
  Entoprocta 78  
The Lophophore Bearers 78  
  Ectoprocta 78  
  Phoronida 78  
  Brachiopoda 79  
The Mollusks 79  
  Mollusca 79  
More Wormlike Phyla 81  
  Sipuncula 81  
  Echiurida 82

- Pogonophora 82
- Hemichordata 82
- Chaetognatha 83
- Segmented Animal Phyla 83
- Annelida 83
- Arthropoda 83
- Radial Symmetry Revisited 86
- Echinodermata 86
- The Chordates 87
- Chordata 87
- Summary 90
- Review Questions 90
- Questions for Further Discussion 91
- Suggestions for Further Reading 91

## Chapter 4

### Marine Primary Producers 93

- Box 4 Microscopes The Small View 94
- Phytoplankton 95
  - Cyanobacteria 96
  - Chrysophyta 98
  - Dinophyta 102
  - Other Phytoplankton 106
  - Special Adaptations for a Planktonic Existence 106
  - Size 107
  - Sinking 108
  - Adjustments to Unfavorable Environmental Conditions 108
- Benthic Autotrophs 109
  - Unicellular Forms 110
    - Cyanobacteria 110
    - Benthic Diatoms 111
  - The Seaweeds 112
    - Photosynthetic Pigments 113
    - Structural Features of Seaweeds 114
    - Reproduction and Growth 117
  - Anthophyta 121
  - Geographical Distribution 123
  - Plant-Dominated Marine Communities 124
- Summary 126
- Review Questions 127
- Questions for Further Discussion 127
- Suggestions for Further Reading 127

## Chapter 5

### Primary Production in the Sea 129

- Measurements of Primary Production 131
- Box 5 Oceanography from Space 134
- Factors That Affect Primary Production 136
  - Light 136
  - Photosynthetic Pigments 140
  - Nutrient Requirements 143
  - Nutrient Regeneration 145
  - Grazing 150
- Seasonal Patterns of Marine Primary Production 153
  - Temperate Seas 153
  - Warm Seas 155
  - Coastal Upwelling 155
  - Polar Seas 155
- Box 6 El Niño 156
- Predictive Modeling 158
- Global Marine Primary Production 158
- Summary 162
- Review Questions 162
- Questions for Further Discussion 162
- Suggestions for Further Reading 163

## Chapter 6

### Estuaries 165

- Introduction 166
- Types of Estuaries 167
- Estuarine Circulation 170
- Salinity Adaptations 171
- Sediment Transport: Creating Habitats 174
- Estuarine Habitats and Communities 174
  - Temperate Wetlands: Salt Marshes 175
  - Tropical Wetlands: Mangals 176
  - Mudflats 177
  - Channels 178

- Economic Uses of Estuaries 179
- The Chesapeake Bay System 181
- Box 7 Estuaries and Eagles: The Columbia River 182
- Summary 186
- Review Questions 187
- Questions for Further Discussion 187
- Suggestions for Further Reading 188

## Chapter 7

### Benthic Communities 189

- Living Conditions on the Bottom 190
  - Seafloor Characteristics 190
  - Animal-Sediment Relationships 195
  - Larval Dispersal 197
- Subtidal Communities 202
  - Shallow Muddy Bottoms 202
  - The Abyss 203
  - Deep-Sea Hot Springs 207
- Summary 212
- Review Questions 212
- Questions for Further Discussion 212
- Suggestions for Further Reading 213

## Chapter 8

### Intertidal Communities 215

- Tides 216
- Intertidal Communities 218
  - Rocky Shores 223
    - The Upper Intertidal 223
    - The Middle Intertidal 226
    - The Lower Intertidal 231
  - Sandy Beaches and Muddy Shores 235
- Summary 241
- Review Questions 242
- Questions for Further Discussion 242
- Suggestions for Further Reading 242

## Chapter 9

### Coral Reefs 245

- Reef-Forming Corals 246
- Reproduction in Corals 253
- Zonation on Coral Reefs 253
- Symbiotic Relationships in Coral Reef Fish 257
- Coloration in Coral Reef Fish 261
- Summary 263
- Review Questions 264
- Questions for Further Discussion 264
- Suggestions for Further Reading 264

## Chapter 10

### Zooplankton 265

- Zooplankton Groups 266
- The Pelagic Environment 270
- Vertical Migration 273
- Feeding 277
- Summary 281
- Review Questions 281
- Questions for Further Discussion 281
- Suggestions for Further Reading 281

## Chapter 11

### The Nekton 283

- The Vertebrates 284
- Vertical Distribution of Nekton 285
- Buoyancy 288
  - Gas Inclusions 288
    - Rigid Gas Containers 288
    - Nonrigid Gas Inclusions 290
- Locomotion 295
  - Body Shape 296
  - Fins 297
    - Caudal Fins 298
    - Paired Fins 299
    - Anal and Dorsal Fins 300
    - Propulsion by Other Nekton 300
  - Speed 300
  - Schooling 304

- Migration 306
  - Some Examples of Extensive Oceanic Migrations 307
  - Orientation 312
- Sensory Reception 314
  - Chemoreception 315
  - Vision 315
  - Equilibrium 316
  - Sound Reception 317
  - Electroreception and Magnetoreception 318
- Reproduction 320
  - Nonseasonal Reproduction 320
  - From Yolk Sac to Placenta 321
  - Some Alternatives to Conventional Sex Ratios 324
- Summary 326
- Review Questions 327
- Questions for Further Discussion 327
- Suggestions for Further Reading 328

## Chapter 12

### Marine Tetrapods 329

- Marine Birds and Reptiles 331
- Box 8 Cetacean Intelligence 334
- Marine Mammals 335
  - Echolocation 342
  - Respiratory and Circulatory Adjustments to Diving 349
  - Temperature Regulation 355
  - Reproduction 356
- Summary 365
- Review Questions 365
- Questions for Further Discussion 366
- Suggestions for Further Reading 366

## Chapter 13

### Fisheries 369

- A Brief Survey of Marine Food Species 370
- Major Fishing Areas of the World Ocean 374
- Box 9 Drift Nets 375

- A Perspective on Marine Sources of Food for Humans 377
- Mariculture 382
- Moving down the Food Chain 382
- The Problems of Overexploitation 383
- The Peruvian Anchoveta 384
- The Great Whales 386
- The Tragedy of Open Access 389
- International Regulation of Fisheries 390
- Summary 392
- Review Questions 392
- Questions for Further Discussion 393
- Suggestions for Further Reading 393

## Chapter 14

### Ocean Pollution 395

- Sewage 396
- Toxic Pollutants 400
  - Anti-Fouling Paints 400
  - DDT 400
  - Dioxins 402
  - PCBs 402
- Oil on Water 403
- Marine Debris 405
  - Fishing Gear 405
  - Plastics 406
- Concluding Thoughts: Developing a Sense of Stewardship 407
- Summary 408
- Review Questions 408
- Questions for Further Discussion 409
- Suggestions for Further Reading 409

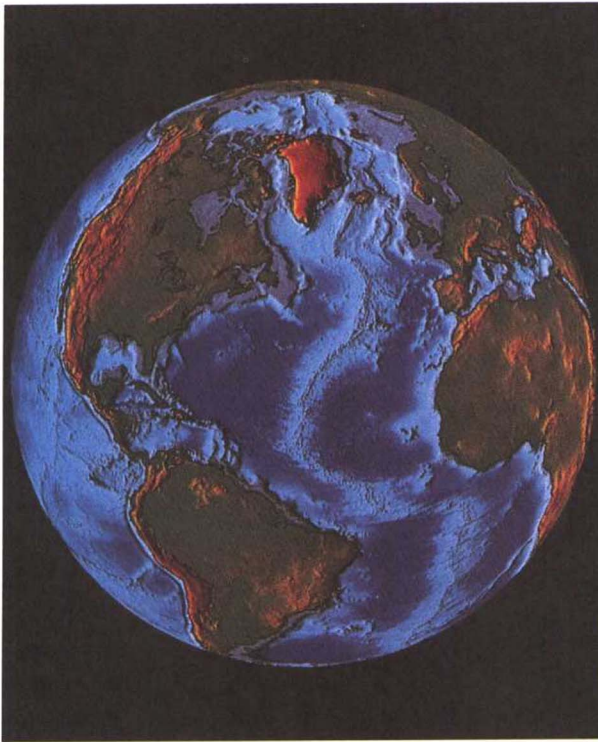
- Appendix A: The Metric System 410
- Appendix B: Some Basic Elements and Atoms 413
- Appendix C: Regional Field and Identification Guides for Marine Organisms 414
- Selected References 415
- Glossary 426
- Taxonomic Index 434
- Subject Index 438

# The Ocean as a Habitat

## Chapter



## 1



A synthetic satellite view of the North Atlantic Ocean Basin

Courtesy National Aeronautics and Space Administration

### THE CHANGING MARINE ENVIRONMENT

#### *Box 1* THREE VOYAGES IN DIFFERENT DIMENSIONS

### THE WORLD OCEAN

### PROPERTIES OF SEAWATER

#### *PURE WATER*

- Viscosity and Surface Tension
- Density-Temperature Relationships
- Heat Capacity
- Solvent Action

#### *SEAWATER*

- Dissolved Salts
- Marine Temperatures
- Salinity-Temperature-Density Relationships
- Dissolved Gases and Acid/Base Buffering
- Dissolved Nutrients

### THE OCEAN IN MOTION

#### *WAVES*

#### *SURFACE CURRENTS*

#### *VERTICAL WATER MOVEMENTS*

### CLASSIFICATION OF THE MARINE ENVIRONMENT

### SUMMARY

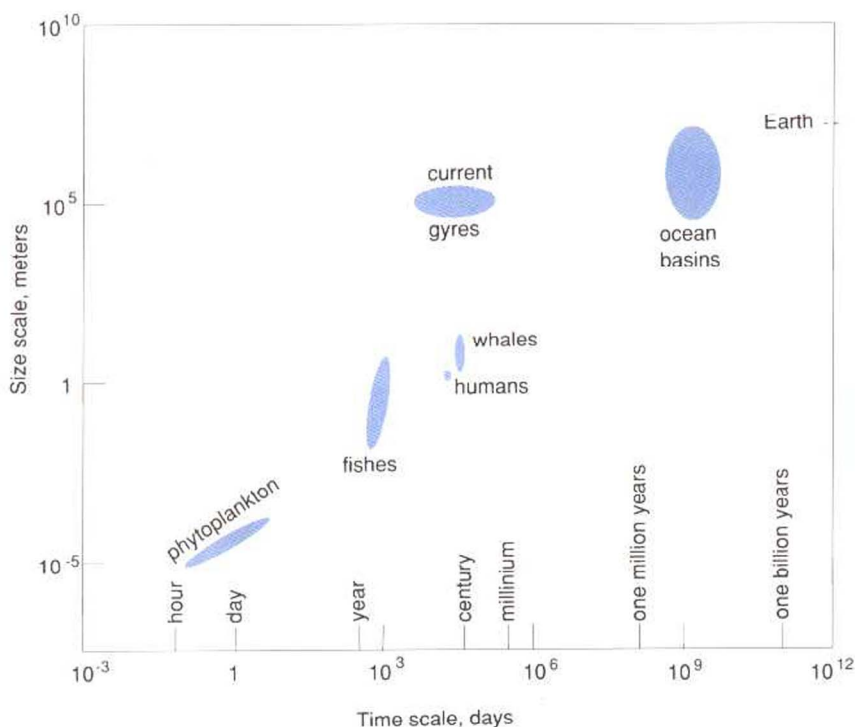
### REVIEW QUESTIONS

### QUESTIONS FOR FURTHER DISCUSSION

### SUGGESTIONS FOR FURTHER READING

**Figure 1.1**

Some important marine features with appropriate time and size scales



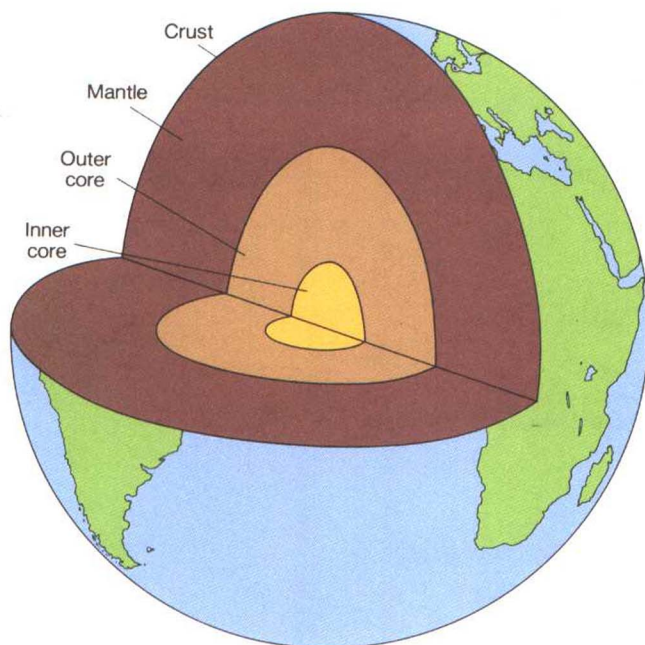
**T**he ocean environment is home to a tremendous variety of living organisms highly adapted to the special conditions of the sea. The general features of these organisms and the variety of marine life itself are products of the many properties of the ocean habitat. This chapter will provide a survey of the developmental history and present geography of the ocean basins and a general discussion of some properties of seawater and of ocean circulation processes.

You need to develop a special perspective to study the oceans. We naturally tend to see the world from a human viewpoint, with human scales of time and distance. To begin to understand the marine environment of earth and how it evolved to its present form, you must broaden your perspective to include very different time and distance scales. Terms such as young and old or large and small have limited meaning unless placed in some manageable context. Figure 1.1 compares space and time scales for a few common oceanic features and inhabitants. Throughout this book, these scales will be revisited and others will be introduced to help you develop a practical sense of the time and space scales experienced by marine organisms.

## *The Changing Marine Environment*

Our solar system, including the earth, is thought to have been formed approximately 4.7 billion years ago. Modern theories on the origin of the solar system suggest that the planets aggregated from a vast cloud of cold gas and dust particles into clusters of solid matter. These clumps continued to grow as gravity attracted them together. As the earth grew in this manner, pressure





Layer	Depth range (km)	Thickness (km)	Density (g/cm <sup>3</sup> )
Crust			
Continental	10-65	55	2.8
Oceanic		10	3.0
Mantle	65-2900	2835	4.5
Outer core	2900-5300	2400	11.5
Inner core	5300-6370	1070	13.0
Total earth	0-6370	6370	5.5

**Figure 1.2**

A section through the earth, showing its density-layered interior structure. The crustal thickness is greatly exaggerated in order to show continents and ocean basins at this scale.

from the outer layers compressed and heated the earth's center. Aided by heat from decay of radioactive elements, the interior of the earth melted. Iron, nickel, and other heavy metals settled to the core, while the lighter materials floated to the surface and cooled to form a thin crust (figure 1.2).

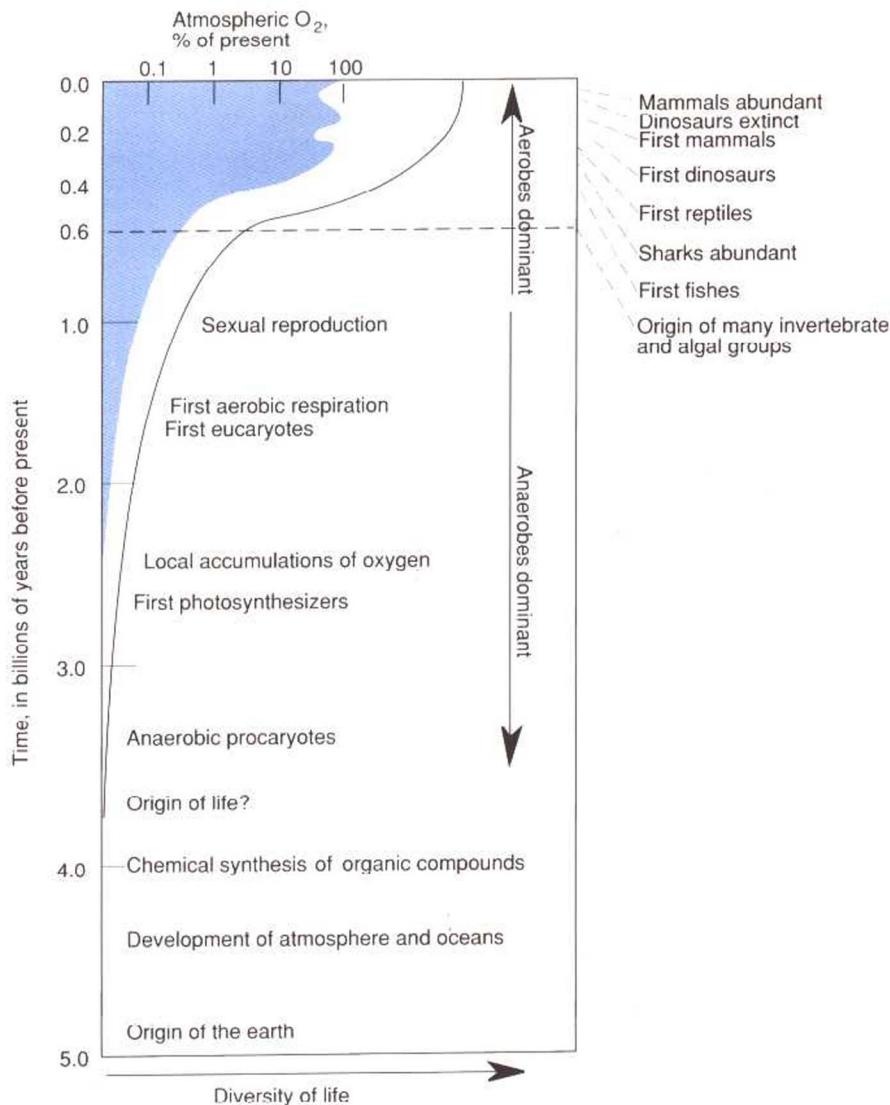
Numerous volcanic vents poked through the crust and tapped the upper mantle for liquid material and gases that were then spewed out over the surface of the young earth, and a primitive atmosphere developed. Water vapor was certainly present. As the water vapor condensed, it fell as rain, accumulated in depressions on the earth's surface, and formed embryonic oceans. Atmospheric gases dissolved into accumulating seawater, and ions, dissolved from rocks and carried to the seas by rivers, added to the mixture, eventually creating seawater.

Since their initial formation, ocean basins have experienced considerable change. New material derived from the earth's mantle has extended the continents so that they are now larger and stand higher than at any time in the past. The oceans have kept pace, getting deeper with accumulations of juvenile water from volcanic gases and of chemical breakdown of rock. Earth's early life forms (represented by fossils older than about one billion years) had a significant impact on the character of their physical environment. Free oxygen (O<sub>2</sub>) was produced in increasing amounts by microscopic photosynthetic cells. The O<sub>2</sub> content of the atmosphere 600 million years ago was probably about 1% of its present concentration. It was not much, but it is believed to have been the turning point, the time when organisms utilizing O<sub>2</sub> (in aerobic respiration) became dominant and organisms not utilizing O<sub>2</sub> became less prevalent.

The evolution of more complex life-forms using increasingly efficient methods of energy utilization set the stage for an explosion of marine life forms. By 500 million years ago, most major groups of marine organisms had made

**Figure 1.3**

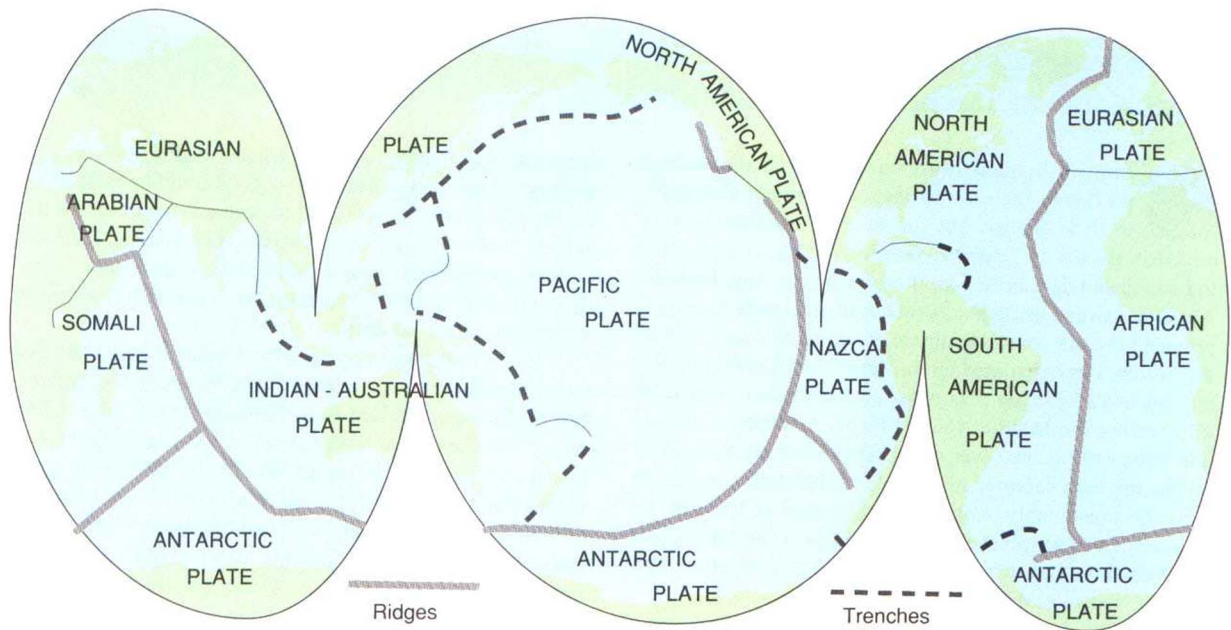
A summary of some biological and physical milestones in the early development of life on earth. The lower curve represents the relative diversity of life; the upper curve represents the  $O_2$  concentration of the atmosphere. Several of the terms used here will be defined in Chapter 2.



their appearance. Worms, sponges, corals, and the immediate ancestors of terrestrial animals and plants were abundant. But life could only exist in the sea at that time, where a protective blanket of seawater shielded it from harmful ultraviolet radiation.

As  $O_2$  became more abundant in the upper atmosphere, some of it was converted to **ozone** ( $O_3$ ). The process of forming ozone absorbed much of the lethal ultraviolet radiation coming from the sun and prevented the radiation from reaching the earth's surface. The  $O_2$  concentration of the atmosphere 400 million years ago is estimated to have reached 10% of its present level. The ozone derived from the additional  $O_2$  screened out enough ultraviolet radiation to permit a few life-forms to abandon their sheltered marine home and colonize the land. Only recently have we become aware that industrialized society's increasing use of aerosols, refrigerants, and other pol-





**Figure 1.4**

The major plates of the earth's crusts. Trenches are shown with dashes, ridges and rises with hatching. Compare the features of this map with those of figures 1.9 and 7.21.

lutants is gradually depleting this protective layer of ozone. Figure 1.3 summarizes significant events of the origin and early development of life on earth.

In the early part of this century, Alfred Wegener proposed that the oceans were changing in other ways. Wegener developed a detailed hypothesis of **continental drift** to explain several global geological features, including the remarkable jigsaw-puzzle fit of some continents (especially Africa and South America). He proposed that our present continental masses had drifted apart following the breakup of a single supercontinent, **Pangaea**. His evidence was ambiguous, and most scientists remained unconvinced. It was not until the early 1960s that new and telling evidence elicited wider endorsement by the scientific community. The early cruises of the *Glomar Challenger* (box 1.1) provided the telling evidence that verified Wegener's hypothesis.

The evidence that supports the closely related concepts of **seafloor spreading** and **plate tectonics** indicates the earth's crust is divided into a number of giant irregular plates (figure 1.4). These rigid plates float on the more dense and slightly plastic mantle material. Each plate is bounded by oceanic trench and ridge systems, and some plates include both oceanic and continental crusts. New oceanic crustal material is formed continually along the axes of oceanic ridges and rises. As the crustal plates grow on either side of the ridge, they move laterally in opposite directions, carrying bottom sediments and attached continental masses with them (figure 1.5).

In 1977, a remarkable discovery of new marine animal communities associated with seafloor hot water vents was made by scientists working in the deep-diving research submersible, *Alvin*. These vents are integral parts of some oceanic ridge or rise systems (figure 7.21). Members of these and other recently discovered deep-sea communities are discussed in chapter 7.

The changes that seafloor spreading and plate tectonics have wrought on the shapes and sizes of the oceans have been impressive. The African continent is drifting northward on a collision course with Europe, relentlessly



## Box 1 Three Voyages in Different Dimensions

**P**rimitive humans must have explored the marine portion of their immediate environment very early in their history, but few of their discoveries were recorded. By 325 B.C., Pytheas, the Greek explorer, had sailed to Iceland and developed a method for determining **latitude**. About a century later, Eratosthenes of Alexandria, Egypt, provided the first known estimate of the earth's size, its first dimension. His calculated circumference of 45,000 km was only about 12% greater than today's accepted value of 40,000 km. During the Middle Ages, Vikings, Arabians, Chinese, and Polynesians sailed over major portions of earth's oceans. By the fifteenth century, all the major inhabitable land areas were occupied; only Antarctica remained untouched by humans. Even so, precise charting of the ocean basins had to await three key developments, each one associated with its own voyage of discovery.

Between 1768 and 1779, James Cook, the English navigator, conducted three exploratory voyages, mostly in the Southern Hemisphere. He was the first to cross the Antarctic Circle and to understand and conquer scurvy (a disease caused by a deficiency of vitamin C). He is best remembered as the first global explorer to make extensive use of the marine **chronometer** developed by John Harrison, a British inventor. The chronometer, a very accurate shipboard clock, established the **longitude** of any fixed point on the earth's surface. Together with Pytheas's 2000-year-old

technique for fixing latitude, accurate positions of geographic features anywhere on the globe could be established for the first time, and our two-dimensional view of the earth's surface was essentially complete. Today, coastal LORAN stations and satellite-based positioning systems permit individuals to determine their position to within a few tens of meters anywhere on earth.

In 1882, one century after Cook's voyages, the first truly interdisciplinary global voyage for scientific exploration of the seas departed from England. The H.M.S. *Challenger* was converted expressly for this voyage. The voyage lasted over three years, sailed almost 125,000 km in a circumnavigation of the globe, and returned with such a wealth of information that fifteen years and fifty large volumes were required to publish the findings. During the voyage, 492 depth soundings were made. These soundings traced the outlines of the Mid-Atlantic Ridge, plumbed the Mariannas Trench to a depth of 8185 m, and filled in rough outlines of the third dimension of the world ocean, its depth.

In 1968, a new and unusual ship, the *Glomar Challenger*, was launched to probe time, the fourth dimension of the oceans. Equipped with a deck-mounted drilling rig, the *Glomar Challenger* was capable of drilling into the seafloor in water over 7000 m deep. Within two years, the *Glomar Challenger* recovered vertical sediment core samples from enough sites on both sides of the Mid-Atlantic

